Increasing the Efficiency and Productivity of the State's Groundwater Monitoring Program

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South Carolina Department of Natural Resources

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Problem Statement

The South Carolina Department of Natural Resources (SCDNR) routinely collects ground-water level data for water-resource assessments and for management and planning purposes. SCDNR's current groundwater-monitoring network consists of 168 wells located at 75 different sites across the State (a map of the network can be found in Appendix A). Most wells (133) are equipped with automatic-data recorders (ADRs) that record water levels every hour while the remaining wells are manually measured. Each site must be visited periodically to download data, to troubleshoot or replace malfunctioning equipment, and to take manual measurements that are used to ensure instruments are calibrated correctly. Current standard operating procedures (SOPs) dictate that each well must be visited six times per year or once every two months. The SOPs for the Groundwater Monitoring Network are located in Appendix B. The collected data are checked for quality assurance and inputted into an Oracle database after each visit. The selection of six site visits per year was to ensure that malfunctioning equipment was replaced or repaired on a periodic basis to reduce the amount of lost data. Currently there are three hydrologists who are responsible for wells in three different regions of the State (Piedmont, Midlands and Coastal).

Owing to both limited staff to maintain the network and the location of a substantial number of sites far away from field offices, each staff person spends a great deal of time visiting the sites and maintaining the groundwater database. The effort exerted just to collect the data and maintain the equipment causes time to be taken away from other job duties, which include data analysis, report preparation, and the development of applications that effectively disseminate groundwater information to stakeholders and the general public. The mission of the Hydrology Section is to "provide guidance, counsel, and data to the State government and the general public for the beneficial use, conservation, and management of South Carolina's water resources" (http://www.dnr.sc.gov/water/hydro/index.html). The amount of resources that go into data collection as opposed to data analysis, report writing, and end user products limits the Hydrology Section's ability to fulfill its mission statement.

The purpose of this project is to investigate the potential for modifying existing SOPs by reducing the number of required site visits per year while maintaining the same level of data quality. Data quality, as used in this study, is defined as the percentage of data gaps, or periods where no to low-quality data is collected. Gaps can be caused by malfunctioning equipment, improper equipment calibration, vandalism, or user error in the process of programming the equipment or downloading data. An example of a data gap for a representative well is illustrated in Appendix C. If less field time can be applied to the data collection efforts and hydrology staff can focus on other work tasks, then the groundwater program should be able to increase its overall efficiency and provide additional products or information that can be used by water resource managers in the State. A critical component of this study is to establish a baseline of missing data that currently exists in the network from which to evaluate changes to the SOPs.

This project, if successful, will allow the Hydrology section to better fulfill its mission statement to "provide guidance, counsel, and data to the State government and the general public…". There are three specific ways this would be accomplished:

1. The network data are used to identify short- and long-term changes in groundwater levels and storage as a result of changes in withdrawals, recharge rates, and climatic conditions; to calibrate groundwater flow models; and to determine regional hydraulic gradients and groundwater flow rates and directions of the major aquifers. The data are vital for assessing current and future groundwater availability in the State and used to support

ongoing water planning and management efforts. Ensuring data integrity, while improve work efficiency, should elevate the success of the State's groundwater planning and management.

2. Though the statewide network includes 168 wells, there are many areas in the State that currently lack adequate groundwater monitoring that can be used by water resource managers. The groundwater program is constantly seeking to add wells to the network that can provide data in areas where groundwater information is not available. As new wells are added to the network, additional staff time is required to maintain the new sites. If the amount of field time can be reduced, by lowering the number of required site visits, then adding new wells will be less of a constraint on staff time.
3. As discussed above, the effort exerted to maintain the network limits the amount of time dedicated to other job duties, which includes the public dissemination of the groundwater information. The mission of the groundwater program, in part, is to provide reliable information to decision-makers. Though the program has historically collected a great deal of quality data, this information has not consistently been made available or presented to decision makers in effective ways. By reducing the amount of time doing field work, staff can focus on improving the dissemination and interpretation of the data though data-analysis reports and the development of tools or applications that present groundwater data to decision-makers.

Gap Statement

The desired outcome or future state of this project is to reduce the amount of field time and cost dedicated to the State's groundwater monitoring network by 25% of the current state (this is approximately equivalent to reducing the number of site visits by 1-2 visits per year), while maintaining the same level of data quality.

Data Collection

A key goal in determining the feasibility of the future state was to characterize the nature of historic data gaps in the network (current state) and determine the prevailing causes for these data gaps. If data gaps were primarily caused by circumstances under which staff hydrologists have much control over as opposed to circumstances beyond their control, then there is good potential for reducing the number of site visits as long as appropriate measure are taken to maintain long-term data quality. Another goal of the data collection was to quantify the amount of time and the total cost per site visit cycle and per year to determine actual cost and time savings if the number of site visits were reduced. A third goal of the data collection efforts and methodology was to research groundwater monitoring networks administered in other states to inform any changes to the agency's current SOPs. Data needed to fulfill these goals are discussed below.

Number and Duration of Data Gaps

A data gap is defined by one or more missing days of average daily groundwater level information. This information was collected by reviewing the groundwater data for each well in the groundwater database to identify the data gaps. Data gaps were assessed over a five year period from January 1st, 2013 through December 31st, 2017. A start date of January 1st, 2013 was chosen because this was the approximate date at which much of the groundwater network was transitioned to a new brand of data logger that had proved to be much more reliable as compared to the previous brand. The information was used to establish a baseline on the amount of missing data. Data was collected by region (Piedmont, Midlands and Coastal) and inputted into Excel spreadsheets.

Causes of Data Gaps

This information was collected from field notes that are taken at each well during a site visit. Causes of data gaps can be classified into two types: 1) "external" or due to circumstances out of a user's direct control, which includes faulty or failing loggers and 2) "internal", or circumstances under a user's direct control, which includes the failure to program loggers correctly or improperly calibrating the equipment. In either type of cause, increasing the time between site visits has the potential to increase the number and maximum duration of data gaps since site or equipment issues may not be identified as frequently. Internally caused data gaps, however, can be minimized by additional training or accountability measures; and if it is determined that most data gaps are internally caused, then there is less risk to impacting data quality by reducing the number of site visits. Hence, the data was used to assess whether reducing the number of site visits (and subsequently increasing the period of time between visits) will lead to additional or longer duration data gaps. The causes were determined for each region (Piedmont, Midlands and Coastal) and documented in Excel spreadsheets.

Total Time Commitment and Cost per Site Visit run

There are three staff hydrologists (including the author of this report) who are responsible for three different regions of the State. Each hydrologist determined the amount of time and mileage needed to complete one cycle of site visits in their respective region. The amount of time includes travel time from site to site, the time needed at each site to collect data and perform site maintenance, and time needed to apply quality control and quality assurance, data processing and data entry. For a given hydrologist, a cycle of site visits includes a collection of routes taken over multiple days that have been planned to optimize (reduce) travel time. This travel time was estimated from Google Maps by each hydrologist. The time required to perform data quality assurance and quality control, data processing and data entry for each hydrologist's assigned wells was also estimated by each hydrologist based on past experience.

The cost per site visit run includes two parts. The first part includes the salary (base and fringe) costs associated with each hydrologist based on the number of work hours determined by each hydrologist as discussed above. The second part includes the fuel and vehicle maintenance costs. These costs were estimated by multiplying the number of miles travel by a factor of $0.535 per mile, which is the rate typically used by the agency for budgeting purposes.

These data were used to determine the current baseline cost and time commitment from which to compare how much money and time would be saved by reducing the number of site visits per year.

Documentation of other state's monitoring programs and associated SOPs

Information about other state's groundwater monitoring programs was collected and was used to inform potential changes to the SCDNR's SOPs. This information was gathered via a survey of groundwater program managers in other states. Survey questions included how often well sites were visited each year, whether or not their program had SOPs, and whether their SOPs included restrictions on the number of allowable data gaps in their networks. Survey questions are included in Appendix D, and the survey was administered online using the SurveyMonkey application.

Data Analysis

Data Gap Analysis

A five year study period from January 1st, 2013 to December 31st, 2017 was chosen for the data gap analysis. A number of wells were added to the network over this five year period, and thus, did not have a five full year record from which to review. The data was filtered to include only those wells that had a full two years of data or that were added to the network prior to 2016. A total of 121 wells remained after filtering. In addition, due to staff limitations during 2013 and 2014, the Coastal region was a low priority, and in order to avoid skewing results, data for the Coastal region was excluded in the analysis for these two years.

For each region (Piedmont, Coastal and Midlands), the percent of missing days was computed by dividing the total number of missing days by the total number of data days for each year and for the entire period of record (2013-2017 for the Piedmont and Midlands regions and 2015-2017 for the Coastal region). A data day is defined as a day in which a daily average water level should have been collected at a well site. Percentages were compared among the regions as opposed to the total number of missing days because the number of wells in each region varied significantly. Appendix E includes a table that lists and describes every data gap (well ID, date of gap, number of missing days, cause of gap, etc.) used in this analysis, and Table 1 summarizes the results of the gap analysis for each region and for the whole statewide network. The percent of missing time for the period of record in the Piedmont, Midlands, and Coastal regions was 1.71%, 2.46%, and 3.87% respectively, while the percent of missing days for the whole network is 2.58%. The annual percentage of missing days for a region varied from 0.00% (Piedmont, 2016) to 6.01% (Coastal, 2017) while the percentage of Total Missing Days varied from 2.02% (2016) to 3.43% (2013). It was anticipated that the percentage of data gaps would be 5-10%

prior to the start of this project, and thus, a resulting average of less than 3% exceeded expectations.

Region	Year	2013	2014	2015	2016	2017	2013-2017
Piedmont	Data Days	5475	5475	5475	5490	5475	27390
15 Wells	No. of Gaps	4	5	6	0	4	19
	No. of Missing Days	268	19	123	0	58	468
	% Missing Days	4.89%	0.35%	2.25%	0.00%	1.06%	1.71%
Midlands	Data Days	16060	19710	22265	28182	28105	114322
77 Wells	No. of Gaps	11	15	8	21	12	67
	No. of Missing Days	471	637	243	821	637	2809
	% Missing Days	2.93%	3.23%	1.09%	2.91%	2.27%	2.46%
Coastal	Data Days	n/a	n/a	8395	10585	10585	29565
29 Wells	No. of Gaps	n/a	n/a	6	4	4	14
	No. of Missing Days	n/a	n/a	434	75	636	1145
	% Missing Days	n/a	n/a	5.17%	0.71%	6.01%	3.87%
All Wells	Data Days	21535*	25185*	36135	44257	44165	171277
121 Wells	No. of Gaps	15*	20*	20	25	20	100
	No. of Missing Days	739*	656*	800	896	1331	4422
	% Missing Days	3.43%*	2.60%*	2.21%	2.02%	3.01%	2.58%

* Values computed for Piedmont and Midlands wells only.

Table 1. Summary of data gaps for each region.

Causes of Data Gaps

The cause of each data gap identified during the 2013-2017 period was determined from field notes, database documentation and personal communication with field hydrologists. There were four general categories for data gap causes – Equipment Fail, Vandalism/Other, User Error and Intentional Removal. Several categories were further subdivided into specific subcategories of cause and each cause was classified as an internal or external. Table 2 lists the types of causes and their classification, while Figure 1 depicts the distribution of the general categories.

The User Error category had the highest number of occurrences (52) with the majority of these occurrences caused by programming errors (35). The next highest category was Equipment Fail, which was the cause for 33 data gaps. External errors accounted for 38% of the occurrences of data gaps while internal errors accounted for 62%. Thus, a majority of the data gaps were caused by circumstances under a hydrologist's control.

Category	Number of Occurrences	Subcategory	Number of Occurrences	Classification
Equipment Fail	33	n/a	33	External
Vandalism/other	5	Vandalism	3	External
		Other	2	External
User Error	52	Data Not Processed	4	Internal
		Erased Data	1	Internal
		Installation Fail	11	Internal
		Manual Measurement Error	1	Internal
		Programming	35	Internal
Intentional Removal	10	n/a	10	Internal

Table 2. Sources of data gaps and their classification.

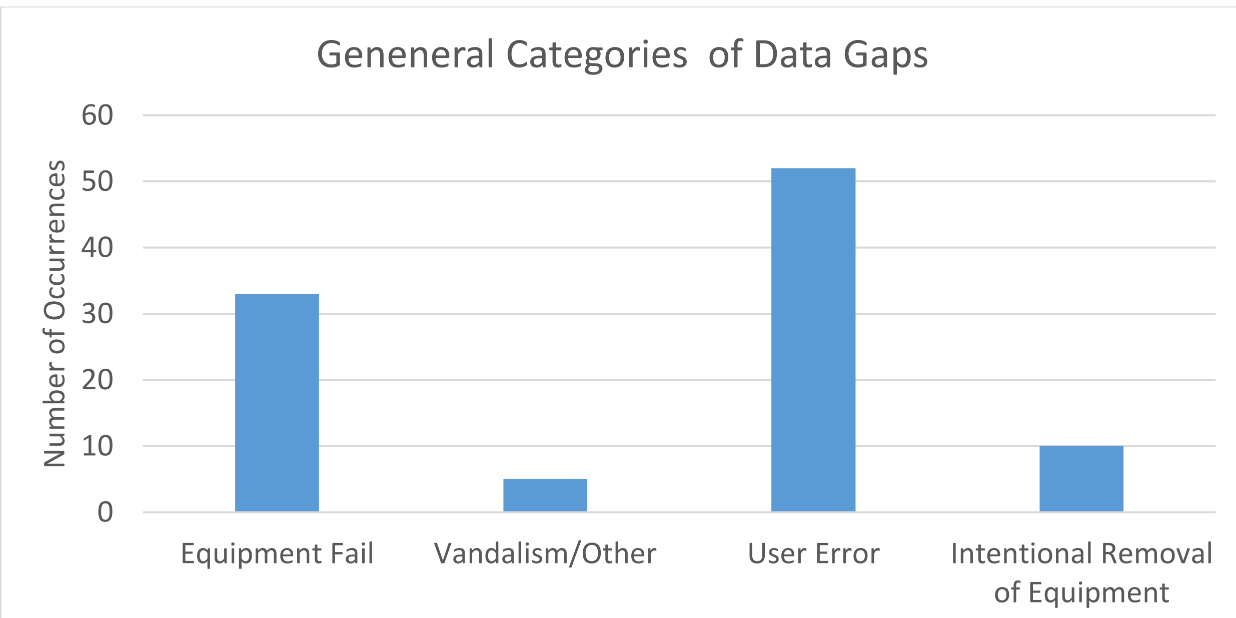


Figure 1. Distribution of Data Gap Causes.

The percentages of missing days due to internal versus external causes were computed for the whole State and summarized in Table 3. The percentage of missing days due to internal errors ranged from 0.55% (2013) to 1.52% (2017) with an average of 1.19% over the 2013-2017 period. The percentage of missing days due to external errors ranged from 0.59% (2016) to 2.88% (2013) with an average of 1.56% over the five year period. Despite the higher number of occurrences of data gaps associated with internal causes, the percentage of actual missing days was higher for gaps associated with external causes. However, a percentage of externally caused data gaps of less than 2% exceeded expectations.

Year	2013	2014	2015	2016	2017	2013-2017
No. of Missing Days						
External	621	514	623	261	659	2678
Internal	118	142	177	635	672	1744
Total	739	656	800	896	1331	4422
Data Days	21535	25185	36135	44257	44165	171277
% External	2.88%	2.04%	1.72%	0.59%	1.49%	1.56%
% Internal	0.55%	0.56%	0.49%	1.43%	1.52%	1.02%
% Missing Total	3.43%	2.60%	2.21%	2.02%	3.01%	2.58%

* Values include data from the Piedmont and Midlands regions only.

Table 3. Summary of missing days due to external and internal causes.

Amount of Time and Total Cost per Site Visit

The amount of time necessary to complete one complete cycle of site visits (including data processing) is shown in Table 4 for each staff hydrologist. Based on typical conditions, staff hydrologists concluded that an average of 3 minutes is needed at a manual site for data collection and an average of 12 minutes is needed for an ADR site. These average times were incorporated into the Total Work Hours column in Table 4. The total amount of time to complete one cycle of site visits statewide is 162.6 hours or 21.7 work days. A total of six visits per site is required under the current SOPs, and the total amount of time dedicated to visiting sites and processing data in a given year is 130 work days. A reduction in the number of site visits from six to four would save a total of 43.4 work days.

Next the total cost per site visit run was determined. The costs associated with each region and the total cost is also presented in Table 4. The total cost for one complete cycle of site visits is $6,972.72 and the total cost per year for six cycles of site visits is $41,836.29. A more detailed budget can be found in Appendix F. A reduction in the number of site visits from six to four would save $13,945.43.

Region	Hourly Salary (including Fringe)	Total Work Hours (field and office)	Total Salary Cost	Total Mileage Cost	Total Cost (1 cycle)	Total Cost (6 cycles)	Total Cost (4 cycles)	Cost Savings (4 cycles)
Piedmont	$ 45.43	24.2	$ 1,099.41	$ 295.21	$ 1,394.62	$ 8,367.71	$ 5,578.48	$ 2,789.24
Midlands	$ 23.91	73.27	$ 1,751.89	$ 843.70	$ 2,595.58	$ 15,573.48	$ 10,382.32	$ 5,191.16
Coastal	$ 33.09	65.17	$ 2,156.48	$ 826.04	$ 2,982.52	$ 17,895.09	$ 11,930.06	$ 5,965.03
Totals	$ 102.43	162.64	$ 5,007.77	$ 1,964.95	$ 6,972.72	$ 41,836.29	$ 27,890.86	$ 13,945.43

Table 4. Summary of work hours and costs associated with maintaining the State's Groundwater Monitoring Network.

Groundwater Monitoring Network Survey Results

The groundwater network survey was sent out to state groundwater managers in 27 states and 17 of these states responded (giving a response rate of approximately 63%). Complete survey results are documented in Appendix D. Survey results indicated that all but two of the 17 respondents had formal SOPs and only three included criteria related to the number and duration of allowable data gaps. The distribution of site visits per year across the states is illustrated in Figure 2. The review of the survey information was complicated by the observation that many states have networks with subsets of wells that are measured or visited on varying time schedules (for examples, see Arizona and Colorado in the Survey results – Appendix D). The number of site visits listed by the 17 respondents range from one per year to 12 per year with a majority of the respondents indicating one to three site visits per year. However, quarterly site visits was the next highest reported rate (7 states). The total number of entries or counts in Figure 2 is greater than 17 because the distribution includes multiple time schedules listed for some states. Drivers listed for the number of site visits per year included legislative mandates, staff limitations, and groundwater management goals of capturing seasonal variations.

Survey results suggested that the SCDNR's current SOP for the number of site visits per year is a more rigorous standard than many other states. In addition, a reduction from six to four site visits per year would remain well within the range of standards reported by other states. There is no evidence in the results that would suggest a reduction in the number of site visits for the SCDNR network would be a cause for concern.

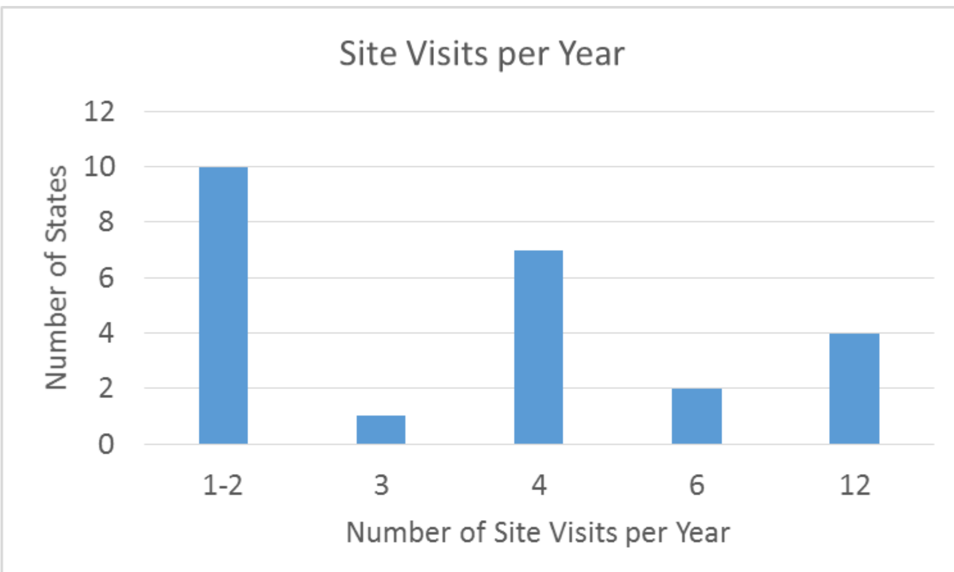


Figure 2. The number of site visits per year reported by 17 other states (total entries are greater than 17 because some states reported multiple schedules for site visits).

Implementation Plan

These results indicate that the goal of reducing the number of site visits from six to four while maintaining data quality is attainable. This reduction in site visits will decrease the amount of time dedicated to maintaining the network by 33%. The time savings will allow the

Groundwater Program to focus on end-user products and applications that can be more readily used by stakeholders in the State.

Current average annual percentage of missing days is approximately 2.6% with the average annual percentage of externally caused gaps averaging less than 2%. Average annual percentage of missing days in the 2-3% range exceeded the expectations of the leadership in the Hydrology Section and is an acceptable level of missing data. A baseline of 2-3% will be used to evaluate future performance with a goal of attaining less than 2% error. In order to reduce the number of site visits from six to four while maintaining a 2-3% baseline, field hydrologists will likely need to reduce the number of internally-caused (user related) data gaps. Approaches to reducing user-error related gaps include additional training and adding the percentage of missing days as a performance metric in the Employee Management Systems' (EPMS) planning stage.

The following action steps will be taken to implement the solution:

1. Make formal changes to the Groundwater Monitoring Network's SOPs to state that the minimum number of site visits per year is four.
2. Make formal changes to the Employee Performance Management System planning stages to reflect that the percentage of missing data for each hydrologist's region will be incorporated into their performance rating.
3. Communicate these changes to appropriate field staff.
4. Identify training needs, if any, and provide training if necessary.

There are no current constraints on the timeline for implementing these changes. Training needs can be identified and addressed within a one to two month period and changes to the SOPs can be applied immediately. It is estimated that by March 2019, a change from six site visits per year to four site visits per year can be fully implemented. There are no external costs or additional funding needed to implement these changes, however, there may be some staff time committed to any training efforts.

One potential obstacle for the chosen solution is the risk associated with increasing the time period between site visits. Increasing the time between site visits can have a negative impact on data quality since any issues at a given site may not be identified as frequently. However, the reduction of internally-caused errors should mitigate this risk.

Internal communication with impacted staff on the SOP modifications is paramount. Initially, the modification to the SOPs will not directly impact any external stakeholders; however, the expected increase in end-user products resulting from these changes should benefit key stakeholders or decision makers in the coming years.

Evaluation Method

In order to assess the success of the proposed solution, an evaluation plan will be developed. A major component of this plan will be an annual audit of the amount of missing data occurring each year. The field hydrologist in each region will be responsible for compiling the number and duration of data gaps each year and will also provide detailed documentation on the causes of these gaps. The data collection methods will be very similar to the methods used to establish the baseline except that data will be collected on an annual basis. Over the next 3-5 years, data quality will be assessed to establish whether the SOP modifications have had a negative impact on quality. Changes in data quality will be assessed by comparing to the 2-3% baseline of missing days as determined from this study.

Summary and Recommendations

A detailed analysis on the number, duration, and causes of data gaps in the SCDNR Groundwater Monitoring Network has been completed to establish a baseline of missing groundwater level data. The period of analysis was 2013-2017. A baseline percentage of missing data was computed to be 2-3%, while less than 2% of the missing data was due to external causes. Based on the results of this analysis, it was concluded that a reduction in the number of site visits per year from six to four would not negatively impact data quality as long as appropriate training and accountability metrics are established. In addition, this reduction in site visits would save the Groundwater Program nearly $14,000 per year. A formal change in the Groundwater Network's SOPs of reducing the number of site visits from six to four is recommended but should only be made if the evaluation plan discussed above is implemented.

Glossary of Terms

Automatic Data Recorder (ADR): Any equipment that can measure groundwater level and store data on a continuous basis. Water levels are measured every hour and daily average water levels are computed from the hourly data.

Cycle: A series of events necessary to collect and process data and to perform site maintenance for each well in the network. Current standard operating procedures require six cycles per year.

Data Day: A day in which a daily average water level should have been collected at a given well that had an ADR installed.

Data Gap: One or more days in which no accurate daily average water level could be computed.

Data Quality: The percentage of missing days computed from the number of missing days divided by the number of data days. Percentages can be computed annually and for the entire period of record.

Equipment Fail: A Data Gap category or cause that involves an ADR’s inability to measure water levels. Equipment fails are related to malfunctions in electronic components, cables or sensors in the ADR instruments.

Intentional Removal: A data gap category or cause that involves the purposeful removal of ADR equipment. ADRs are sometimes removed in order to perform well rehab or to conduct water quality tests.

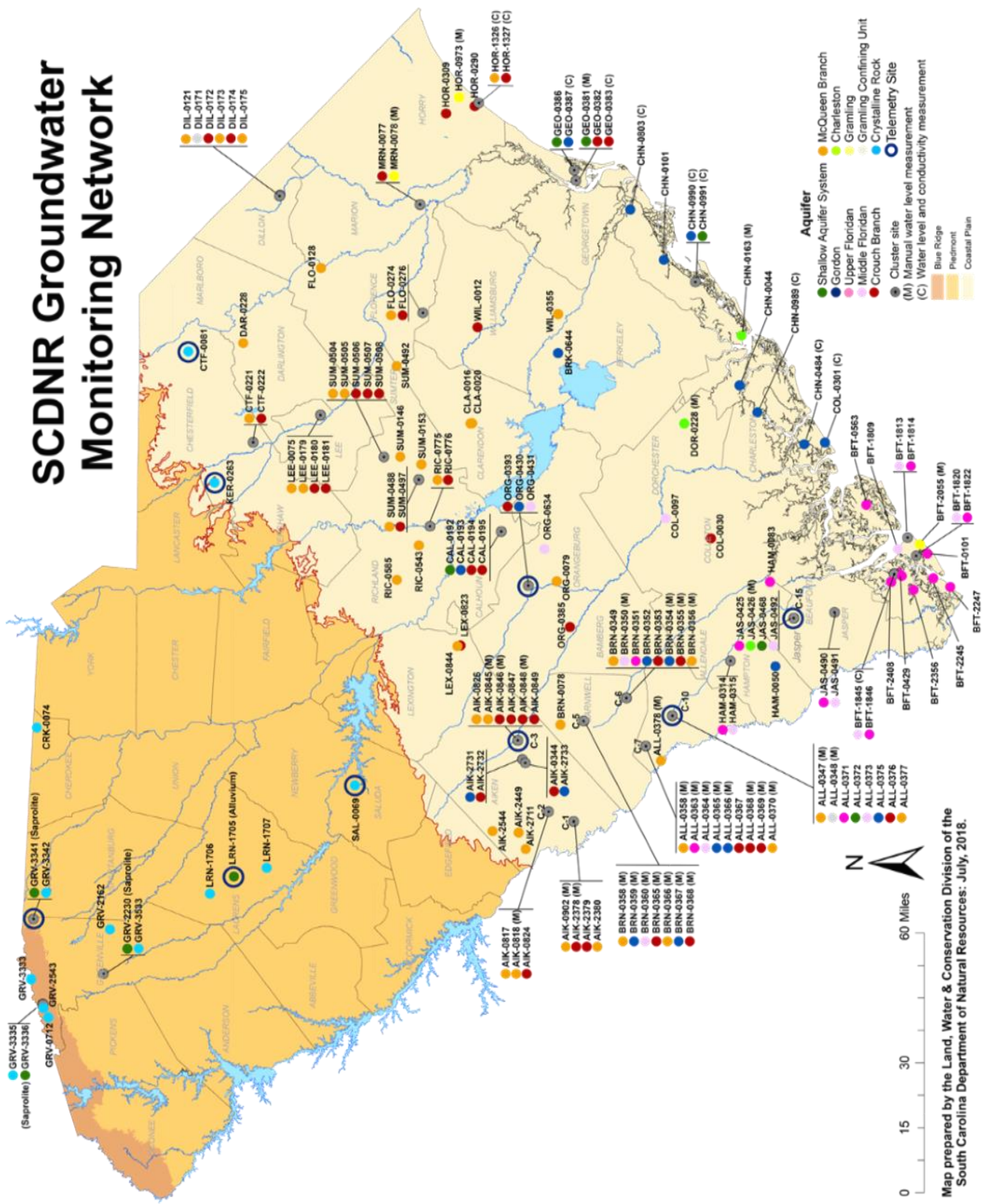
Internal Cause: A data gap classification that relates to circumstances under a user’s direct control or circumstances upon which the user has direct influence.

External Cause: A data gap classification that relates to circumstances beyond a user's direct control or circumstances upon which the user has limited or no direct influence.

Manual Site: A well that does not have an ADR installed but is still visited periodically (currently six times per year) to take a measurement using a water level meter.

User Error: A data gap category or cause that involves a mistake made by the user in programming and/or calibrating ADR equipment or other errors made by a user in collecting and processing data.

Appendix A. South Carolina Groundwater Monitoring Network



Appendix B. Standard Operating Procedures for the South Carolina Groundwater Monitoring Network

Earth Science Group
Land, Water and Conservation Division
South Carolina Department of Natural Resources

By Scott Harder
9/30/13
Updated, 7/23/18

1. Site visits should be made a minimum of 6 times per year, approximately once every two months. Additional site visits may be necessary to repair/replace malfunctioning equipment or do perform additional site maintenance.

2. Appropriate quality control and quality assurance measures should be implemented during each site visit:
    a. For sites with pressure transducers, cable length values should be determined during the time of visit and compared to previous cable length estimates to evaluate the sensor's performance. The cable length value is the sum of 1) the depth of water above probe as measured by the transducer and 2) the depth to water from the measuring point (manual measurement).
    b. For sites with unvented pressure transducers and no barometric instrument installed on site, a measurement must be taken from a spare barometric instrument that is transported from site to site. This measurement will allow an estimate of the depth of water above probe, and thus, an estimate of the cable length value during each site visit.
    c. For transducers with pressure ranges rated at 65 feet (20 meters) or less, ADRs should be replaced if cable length values deviate by more than plus or minus 0.20 ft for two consecutive downloads.
    d. Clock accuracy should be checked during each site visit for each ADR instrument. In most cases, a one or two minute error is acceptable. Clocks off by more than a few minutes should be reset.
    e. For wells that are tidally influenced, the manual measurement and the real-time ADR reading must be collected as close to the same time as possible in order to compute accurate cable length values.

3. Model numbers and serial numbers should be documented for all installed ADRs and associated equipment (direct read cables, for example). Any changes to instrumentation must be clearly documented (date and time of change, reason for change, model and

serial numbers of any instrumentation removed along with model and serial numbers of any instrumentation added).

4. Efforts should be made to ensure that enough inventory is immediately available in the field to replace ADR equipment when needed to avoid the additional loss of data.

5. Under normal circumstances, data collected during a site visit should be checked for quality control and quality assurance or sent to the Columbia office for review within two weeks of the site visit.

6. If ADR instrumentation at a given site is determined to be malfunctioning while reviewing data in the office, efforts should be made to replace or repair the ADR instruments as soon as possible. This may require additional site visits.

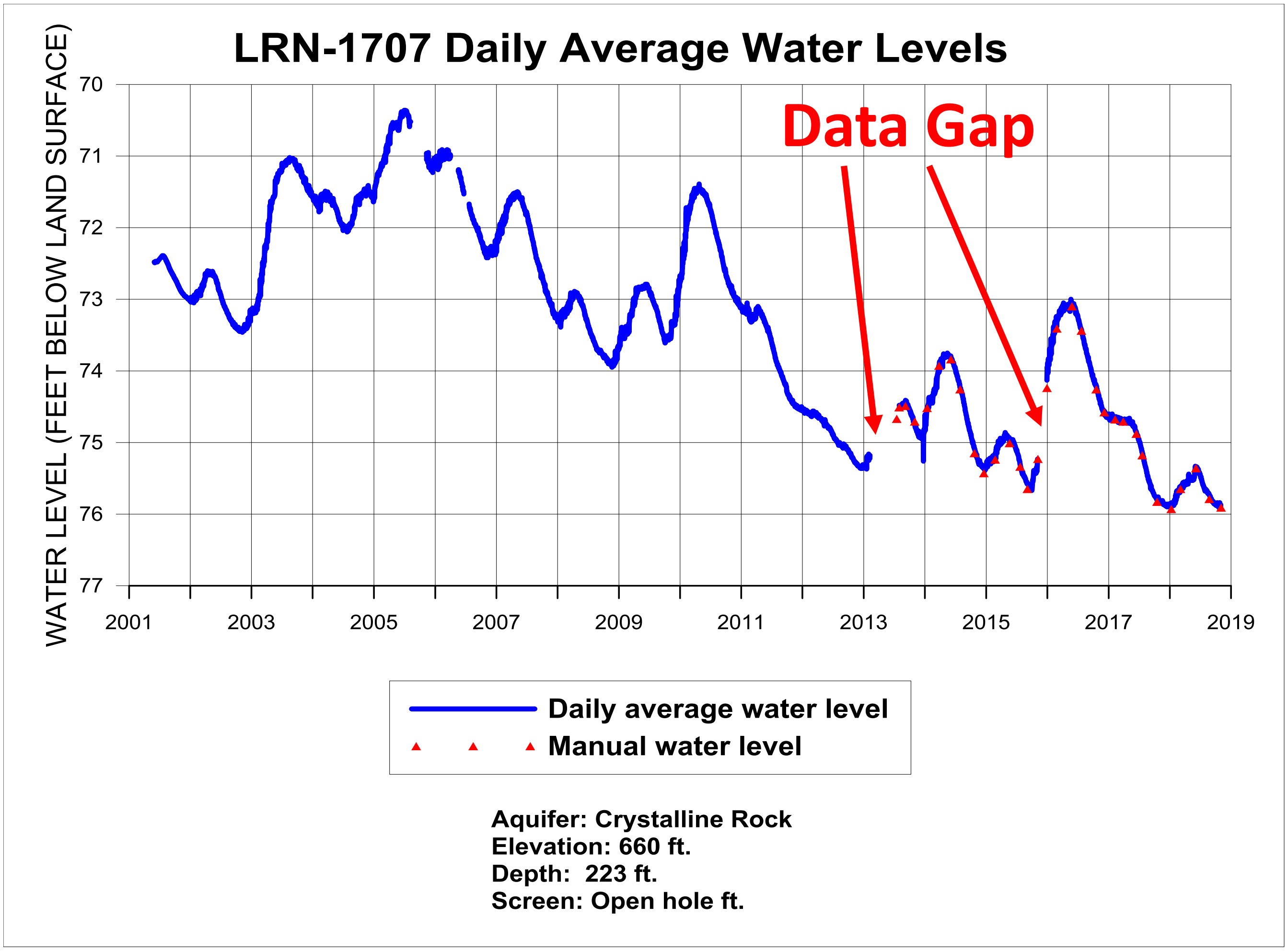
7. Clocks for all instrumentation will be programmed in Eastern Standard Time. Do not correct for Daylight Savings.

8. For sites with vented pressure transducers, desiccant packs must be replaced once every two months to prevent moisture from accumulating in the transducer's vent tube. Excess moisture can cause faulty ADR readings and can potentially damage the transducer.

9. Pressure gages used to measure water levels at freely-flowing wells (wells in which water levels are above ground surface elevation) should be calibrated once per year by a licensed or certified company.

Appendix C. Data Gap Example

A hydrograph for a well located in Laurens County highlighting data gaps is presented below.



Appendix D. South Carolina Department of Natural Resources Groundwater Monitoring Network Survey

The South Carolina Department of Natural Resources (SCDNR) would greatly appreciate your assistance in completing the short survey below. This information will be used to evaluate and improve the efficiency of the SCDNR's Groundwater Monitoring Network. If you have any questions please contact Scott Harder, harders@dnr.sc.gov, or Brooke Czwartacki, czwartackib@dnr.sc.gov.

1. How many wells are included in your monitoring network (those wells measured at least once per year and/or have water level loggers that record continuous data)?
2. How often is each manual and/or continuously recording site visited?
3. Do you have Standard Operating Procedures for your network?
4. Do you have any criteria or goal that limits the amount of allowable data gaps or describes how much data can be lost or otherwise not collected (due to equipment failures, vandalism, user error, etc.)? If so, please describe.
5. How many staff do you have collecting field data, performing site maintenance, and inputting data to associated databases for the wells in the monitoring network?
6. What are the drivers or reasons for the number of site visits you make per year?

What state is your network in?	How many wells are included in your monitoring network (those wells measured at least once per year and/or have water level loggers that record continuous data)?	How often is each manual and/or continuously recording site visited?	Do you have Standard Operating Procedures for your network?	Do you have any criteria or goal that limits the amount of allowable data gaps or describes how much data can be lost or otherwise not collected (due to equipment failures, vandalism, user error, etc.)? If so, please describe	How many staff do you have collecting field data, performing site maintenance, and inputting data to associated databases for the wells in the monitoring network?	What are the drivers or reasons for the number of site visits you make per year?
Alabama	400	2 times a year	yes	not formally. 30 Real-Time Wells are reported daily. Visit site at earliest scheduling if system goes down.	10	Seasonal variation: Fall and Spring
Arizona	1780	Annually-1452; Quarterly-70; Daily-134; Monthly-22; Semi-Annual-100	yes	question skipped	13	AZ Groundwater Management Act
Colorado	1,200	mostly once a year, some twice a year	yes	no	4 full time staff. 5 subcontractors measure and upload approximately 600 water level	Generally we are interested in water levels just before and just after irrigation season. Most of our

					measurements per year	groundwater development is associated with irrigated agriculture.
Delaware	90	usually monthly	yes	we just try to minimize data loss	2 to 3	need and finances
Delaware	130	most quarterly, 5 monthly	yes	Yes, for some things. Most apply to logger collected wl data. Number of observations for a daily mean, allowable differences between logger and manually measured wl. Maintenance of wl tapes. It gets more complicated for how effort is prioritized.	6 different people work on it but less than 0.5 FTE.	Staffing limitations and number of wells to monitor
Georgia	129 monitoring wells are monitored for water level by USGS and funded in part by GA. GA EPD monitors another 124	Wells monitored by water level are maintained by USGS and are visited at least annually.	USGS has an SOPs	USGS monitors of water level and it would be in their QAPP	Unknown - The Cooperative grant is for $680,100 of which GA EPD funds $467,664	Wanting to understand Georgia's ground water sustainability

	drinking water wells for water quality.					
Iowa	60	quarterly	Yes	No, we don't have any criteria like that.	2	The majority of our wells have historic data that was collected by the USGS. The USGS collected quarterly measurements. We wanted to keep things as similar as possible (because it make analyses easier for example). So we went with quarterly collections as well.
Kansas	1,400	Annual wells- once a year. Continuously recorded- quarterly	No but collected data is subject to review and re-measures if needed.	no	Annual network- 16, Continuously measured wells- 2.	Goal for annual network is for regional assessment of the aquifer over time. Continuously monitored wells try to capture variations at the local scale.

Maine	30	between 2 and four times a year	yes	no	2	The original purpose of wells is environmental monitoring at contaminated sites. Each well has its own monitoring frequency depending on environmental needs at the site.
Maryland	480	~245 once/year; ~165 twice/year; ~25 six times/year; ~45 monthly; continuous recorders on <~20	We work in cooperation with the USGS and follow their operating procedures	No formal written criteria, but each well is evaluated on an individual bases against data needs and objectives.	4 at Maryland Geological Survey, and ~4 at USGS MD/DE Water Science Center	Whether the frequency adequately captures trends in water levels related to stresses (climate, withdrawals) for the given objectives (ex. longer-term effects of well development)
Minnesota	1100	at least 6 times per year	yes	no	35	contracts with monitoring partners and maintenance
Missouri	149	Minimum of twice per year-more if there is equipment failure	We have operating procedures, but they are not documente d	If equipmet malfunctions we attempt to correct within two weeks, but the data will still show the gap.	3 state staff collect data and maintain wells. Data is transmitted to USGS to be managed, checked and displayed through a cooperative agreement.	We visit at least twice per year based on equipment manintence requirments.

Montana	800	quarterly	yes	no	3	to catch seasonal variations
New Hampshire	32	Monthly	yes	no	3 personnel involved but only part of their time goes toward our network efforts	Monthly collection is a reasonable labor allocation for colecting consistent data. Our data are principally used to evaluate groundwater conditions during times of drought.
North Carolina	671	Typically 4 times per year to download hourly water levels, perform maintenance, etc.	Yes	Numerous procedures are in place for purposes described	13	Download data, verify data accuracy with tapedowns, and maintain network assets
Oklahoma	900	1 or 3 times a year	yes	Our data collection success rate is very good; if we lose a site, we try to replace it	6	We have annual network measured during Jan-Feb (includes all sites) and a trend network that includes 35 % of the sites that are visited in Jan/May/Sept which is also when we perform maintenance on our continuous sites

Texas	over 7000	at least once a year	yes	We have 2 legislatively mandated measures for our network. 1) Output: set number of measurements entered per fiscal year (each measurement counted even if from same well). 2) Adequacy: formula used to set the number of wells required per county/aquifer combination, based on estimated pumpage values and percentage of land area covered by aquifer.	7 field staff, 2 database staff, 1 manager	money, staff availability, cooperator availability
Utah	100 (water quality only)	once a year	yes	no	8	EPA provides free analysis for 100 total only

Appendix E. Data Gap Documentation

Well	Region	Start Date	End Date	Year	Days	Internal/External	Cause
GRV-3341	Piedmont	8/15/2017	9/14/2017	2017	31	Internal	User Error - Erased Data
GRV-3341	Piedmont	9/16/2017	9/18/2017	2017	3	Internal	User Error - Programming
GRV-3342	Piedmont	12/22/2014	12/31/2014	2014	10	External	Equipment Fail
GRV-3342	Piedmont	1/1/2015	3/2/2015	2015	61	External	Equipment Fail
GRV-3342	Piedmont	9/16/2017	9/18/2017	2017	3	Internal	User Error - Programming
LRN-1705	Piedmont	3/8/2017	3/28/2017	2017	21	Internal	User Error - Programming
LRN-1706	Piedmont	2/8/2013	2/16/2013	2013	9	External	Equipment Fail
LRN-1706	Piedmont	5/10/2013	7/31/2013	2013	83	External	Equipment Fail
LRN-1706	Piedmont	10/4/2015	10/4/2015	2015	1	Internal	User Error - Installation Fail
LRN-1707	Piedmont	2/8/2013	7/31/2013	2013	174	External	Vandalism
LRN-1707	Piedmont	12/29/2013	12/30/2013	2013	2	internal	User Error - Installation Fail
LRN-1707	Piedmont	1/11/2014	1/13/2014	2014	3	internal	User Error - Installation Fail
LRN-1707	Piedmont	3/7/2014	3/8/2014	2014	2	internal	User Error - Installation Fail
LRN-1707	Piedmont	3/17/2014	3/19/2014	2014	3	internal	User Error - Installation Fail
LRN-1707	Piedmont	12/29/2014	12/29/2014	2014	1	internal	User Error - Installation Fail
LRN-1707	Piedmont	1/4/2015	1/5/2015	2015	2	internal	User Error - Installation Fail
LRN-1707	Piedmont	2/26/2015	2/26/2015	2015	1	internal	User Error - Installation Fail
LRN-1707	Piedmont	10/3/2015	10/5/2015	2015	3	internal	User Error - Installation Fail
LRN-1707	Piedmont	11/5/2015	12/29/2015	2015	55	internal	User Error - Installation Fail
AIK-0817	Midlands	04/10/13	05/08/13	2013	29	Internal	Intentional Removal of Equipment
AIK-0824	Midlands	04/10/13	05/08/13	2013	29	Internal	Intentional Removal of Equipment
AIK-0826	Midlands	04/10/13	05/08/13	2013	29	Internal	Intentional Removal of Equipment
AIK-0826	Midlands	04/09/14	05/28/14	2014	50	External	Equipment Fail
AIK-0847	Midlands	04/10/13	05/08/13	2013	29	Internal	Intentional Removal of Equipment
AIK-2449	Midlands	08/10/15	08/25/15	2015	16	Internal	User Error - Programming
AIK-2544	Midlands	08/10/15	08/25/15	2015	16	Internal	User Error - Programming
AIK-2711	Midlands	08/10/15	08/25/15	2015	16	Internal	User Error - Programming
ALL-0367	Midlands	02/04/14	03/20/14	2014	45	External	Equipment Fail
ALL-0367	Midlands	04/30/15	06/25/15	2015	57	Internal	User Error - Programming
ALL-0371	Midlands	03/01/17	05/02/17	2017	63	Internal	User Error - Programming
ALL-0372	Midlands	06/19/13	08/19/13	2013	62	External	Equipment Fail
ALL-0377	Midlands	06/25/15	08/27/15	2015	64	External	Equipment Fail
ALL-0377	Midlands	03/18/16	06/02/16	2016	77	Internal	User Error - Manual Measurement
ALL-0377	Midlands	11/22/17	12/31/17	2017	40	Internal	User Error - Programming
BRN-0349	Midlands	10/09/13	11/25/13	2013	48	External	Equipment Fail
BRN-0351	Midlands	11/22/17	12/31/17	2017	40	Internal	User Error - Programming
BRN-0352	Midlands	11/22/17	12/31/17	2017	40	Internal	User Error - Programming
CAL-0195	Midlands	07/03/14	07/31/14	2014	29	External	Installation Fail - Site
CTF-0221	Midlands	06/05/14	07/31/14	2014	57	Internal	Intentional Removal of Equipment

DIL-0121	Midlands	05/31/13	06/11/13	2013	12	External	Equipment Fail
DIL-0121	Midlands	06/06/14	07/02/14	2014	27	External	Equipment Fail
DIL-0172	Midlands	01/30/15	02/04/15	2015	6	Internal	Intentional Removal of Equipment
DIL-0175	Midlands	07/24/17	09/27/17	2017	66	Internal	User Error - Programming
FLO-0128	Midlands	04/13/14	04/21/14	2014	9	External	Equipment Fail
FLO-0128	Midlands	07/01/15	09/02/15	2015	64	External	Equipment Fail
FLO-0274	Midlands	07/02/13	08/06/13	2013	36	External	Equipment Fail
FLO-0274	Midlands	07/30/14	09/30/14	2014	63	External	Equipment Fail
FLO-0274	Midlands	06/15/16	12/31/16	2016	200	External	Equipment Fail
FLO-0274	Midlands	01/01/17	03/21/17	2017	80	External	Equipment Fail
FLO-0276	Midlands	10/20/13	12/18/13	2013	60	External	Equipment Fail
FLO-0276	Midlands	07/26/17	09/19/17	2017	56	External	Equipment Fail
FLO-0276	Midlands	10/17/17	12/05/17	2017	50	Internal	User Error - Programming
HAM-0050	Midlands	08/25/16	09/22/16	2016	29	Internal	User Error - Programming
HAM-0050	Midlands	11/08/16	12/15/16	2016	38	Internal	User Error - Programming
HAM-0050	Midlands	12/18/16	02/09/17	2017	54	Internal	User Error - Programming
HAM-0083	Midlands	08/25/16	09/22/16	2016	29	Internal	User Error - Programming
HAM-0083	Midlands	11/08/16	12/15/16	2016	38	Internal	User Error - Programming
HAM-0083	Midlands	12/18/16	02/09/17	2017	54	Internal	User Error - Programming
HAM-0314	Midlands	08/08/16	08/10/16	2016	3	Internal	Intentional Removal of Equipment
HAM-0315	Midlands	08/08/16	08/16/16	2016	9	Internal	Intentional Removal of Equipment
JAS-0425	Midlands	08/25/16	11/29/16	2016	97	Internal	User Error - Programming
JAS-0425	Midlands	12/18/16	12/31/16	2016	14	Internal	User Error - Programming
JAS-0425	Midlands	01/01/17	02/09/17	2017	40	Internal	User Error - Programming
JAS-0468	Midlands	08/25/16	09/22/16	2016	29	Internal	User Error - Programming
JAS-0468	Midlands	11/08/16	11/29/16	2016	22	Internal	User Error - Programming
JAS-0468	Midlands	12/18/16	02/09/17	2017	54	Internal	User Error - Programming
JAS-0490	Midlands	08/15/16	08/25/16	2016	11	Internal	Intentional Removal of Equipment
JAS-0490	Midlands	09/12/16	11/30/16	2016	80	Internal	User Error - Programming
JAS-0491	Midlands	08/15/16	08/18/16	2016	4	Internal	Intentional Removal of Equipment
JAS-0491	Midlands	09/12/16	11/30/16	2016	80	Internal	User Error - Programming
JAS-0492	Midlands	08/25/16	09/23/16	2016	30	Internal	User Error - Programming
JAS-0492	Midlands	11/08/16	11/29/16	2016	22	Internal	User Error - Programming
KER-0263	Midlands	11/20/15	11/23/15	2015	4	Internal	User Error - Data Not Processed
ORG-0079	Midlands	08/14/13	10/07/13	2013	55	External	Vandalism
ORG-0079	Midlands	11/14/13	01/02/14	2014	50	External	Installation Fail - Site
ORG-0079	Midlands	10/02/14	10/20/14	2014	19	Internal	User Error - Programming
ORG-0393	Midlands	10/02/14	10/20/14	2014	19	Internal	User Error - Programming
ORG-0430	Midlands	10/02/14	10/20/14	2014	19	Internal	User Error - Programming
ORG-0431	Midlands	10/02/14	10/20/14	2014	19	Internal	User Error - Programming
RIC-0543	Midlands	10/01/14	12/16/14	2014	77	External	Equipment Fail
RIC-0585	Midlands	10/01/14	12/16/14	2014	77	External	Equipment Fail
SUM-0146	Midlands	04/05/16	04/07/16	2016	3	Internal	User Error - Data Not Processed

SUM-0153	Midlands	04/05/16	04/07/16	2016	3	Internal	User Error - Data Not Processed
SUM-0497	Midlands	07/26/13	10/15/13	2013	82	External	Equipment Fail
SUM-0497	Midlands	10/01/14	12/16/14	2014	77	External	Equipment Fail
SUM-0497	Midlands	04/05/16	04/07/16	2016	3	Internal	User Error - Data Not Processed
BFT-0101	Coastal	3/11/2015	3/12/2015	2015	2	External	Equipment Fail
BFT-0101	Coastal	4/30/2015	5/6/2015	2015	7	External	Equipment Fail
BFT-1820	Coastal	3/7/2017	12/31/2017	2017	300	External	Vandalism
BFT-1845	Coastal	8/6/2015	12/31/2015	2015	148	External	Equipment Fail
BFT-1845	Coastal	1/1/2016	2/18/2016	2016	49	External	Equipment Fail
CHN-0989	Coastal	5/4/2017	8/24/2017	2017	113	Internal	User Error - Installation Fail
CHN-0990	Coastal	3/29/2015	4/28/2015	2015	31	External	Equipment Fail
COL-0301	Coastal	7/16/2015	12/31/2015	2015	169	External	Equipment Fail
COL-0301	Coastal	1/1/2016	1/12/2016	2016	12	External	Equipment Fail
COL-0301	Coastal	8/24/2017	12/31/2017	2017	130	External	Equipment Fail
HOR-0290	Coastal	12/1/2016	12/7/2016	2016	7	Internal	User Error - Programming
HOR-0309	Coastal	1/1/2015	3/18/2015	2015	77	External	Equipment Fail
HOR-0309	Coastal	12/1/2016	12/7/2016	2016	7	Internal	User Error - Programming
HOR-0309	Coastal	5/9/2017	8/9/2017	2017	93	External	Equipment Fail

Appendix F. Detailed Budget for the Administration of the Groundwater Monitoring Network

Region	Salary (hourly)	Fringe (Hourly)	Total Salary & Fringe (hourly)	No. of Field Hours (1 cycle)	No. of Data Processing Hours (1 cycle)	Total Work Hours (1 cycle)	Total Salary Cost (1 cycle)	Total Miles Traveled (1 cycle)	Mileage Cost/mile	Total Mileage Cost (1 cycle)	Total Cost (1 cycle)	Total Cost (6 cycles)	Total Cost (4 cycles)	Cost Savings for 4 cycles
Piedmont	$ 31.99	$ 13.44	$ 45.43	14.2	10	24.2	$ 1,099.41	551.8	$ 0.535	$ 295.21	$ 1,394.62	$ 8,367.71	$ 5,578.48	$ 2,789.24
Midlands	$ 16.84	$ 7.07	$ 23.91	49.52	23.75	73.27	$ 1,751.89	1577	$ 0.535	$ 843.70	$ 2,595.58	$15,573.48	$10,382.32	$ 5,191.16
Coastal	$ 23.30	$ 9.79	$ 33.09	42.67	22.5	65.17	$ 2,156.48	1544	$ 0.535	$ 826.04	$ 2,982.52	$17,895.09	$11,930.06	$ 5,965.03
Totals				106.39	56.25	162.64	$ 5,007.77	3672.8		$ 1,964.95	$ 6,972.72	$41,836.29	$27,890.86	**$ 13,945.43**